Deep Caribbean Sea warming

Gregory C. Johnson [a] , Sarah G. Purkey [a,b]

[a]NOAA/Pacific Marine Environmental Laboratory, 7600 Sand Point Way N. E. Bldg. 3, Seattle, WA 98115, USA

[b]School of Oceanography, Box 357940, University of Washington, Seattle, WA 98195, USA

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Abstract

Data collected from hydrographic stations occupied within the Venezuelan and Columbian basins of the Caribbean Sea from 1922 through 2003 are analyzed to study the decadal variability of deep temperature in the region. The analysis focuses on waters below the 1815-m sill depth of the Anegada–Jungfern Passage. Relatively dense waters (compared to those in the deep Caribbean) from the North Atlantic spill over this sill to ventilate the deep Caribbean Sea. Deep warming at a rate of over 0.01 °C decade^{-1} below this sill depth appears to have commenced in the 1970s after a period of relatively constant deep Caribbean Sea temperatures extending at least as far back as the 1920s. Conductivity-Temperature-Depth station data from World Ocean Circulation Experiment Section A22 along 66°W taken in 1997 and again in 2003 provide an especially precise, albeit geographically limited, estimate of this warming over that 6-year period. They also suggest a small (0.001 PSS-78, about the size of expected measurement biases) deep freshening. The warming is about 10 times larger than the size of geothermal heating in the region, and is of the same magnitude as the average global upper-ocean heat uptake over a recent 50-year period. Together with the freshening, the warming contributes about 0.012 m decade^{-1} of sea level rise in portions of the Caribbean Sea with bottom depths around 5000 m.

Keywords: Caribbean Sea; Climate Change; Sea Level Rise; Ocean Warming

1. Introduction

The ventilation of the main deep basins in the Caribbean Sea – the Venezuelan and Columbian basins – is accomplished through an inflow of relatively dense water of North Atlantic origin through the Anegada–Jungfern Passage (Sturges, 1975; Stalcup et al., 1975; Fratantoni et al., 1997; MacCready et al., 1999). The relatively cold, salty, silicic acid-poor, and oxygen-rich water can be found descending into the Venezuelan Basin along its northern edge (Sturges, 1975; Stalcup et al., 1975) and moving west along the boundary. However, away from the inflow region, the water below the sill depth in the Caribbean Sea tends to be relatively homogenous in water properties vertically, but especially horizontally, all throughout the Venezuelan and Columbian basins (Ribbat et al., 1976). Deep basins replenished by an overflow through a single sill often have relatively homogenous properties below their sill depth. The absence of large lateral gradients makes detection of deep variations in the Caribbean Sea relatively robust compared to many other regions in the open ocean (Joyce et al., 1999).

Estimates of the rate of deep inflow into the Caribbean Sea inferred from hydrographic and roughly month-long current meter measurements near and downstream of the passage during the early 1970s are around 0.05×10^6 m^3 s^{-1} (Sturges, 1975; Stalcup et al., 1975). A similar set of observations, but with mooring deployments spanning roughly 14 months during 1991–1992, reports an average inflow of 0.11×10^6 m^3 s^{-1}, with large temporal variations in inflow temperature and transport (MacCready et al., 1999).

Box and one-dimensional models can be used to estimate the vertical diffusivity, κ, needed to maintain a steady state of properties in a deep basin, and even the deep inflow rate, given sufficient constraints. A steady-state box model of deep-water properties in the Venezuelan Basin, including ^{14}C data from 1973, results in estimates of $\kappa = 5 \times 10^{-4}$ $m^2\ s^{-1}$ at 2500 m and an inflow rate of $0.23 \times 10^6\ m^3\ s^{-1}$ (Ribbat et al., 1976), presumably applicable for some decades prior to 1973. However, a one-dimensional model of the Venezuelan and Columbian basins combining observed inflow data from 1991–1992 and a simple model of plume dynamics results in lower values of κ within the deep Caribbean Sea, with $\kappa = 0.3 \times 10^{-4}\ m^2\ s^{-1}$ near the sill depth (MacCready et al., 1999).

The inflow of Atlantic water tends to cool the waters in the deep Caribbean Sea, while downward diffusion of heat from above and geothermal heating from the bottom tends to warm these waters. Observations of bottom heat flux suggest an average geothermal heating around 0.05 W m^{-2} in the deep Caribbean basins (Epp et al., 1970). A more recent study limited to the eastern side of the Venezuelan Basin finds a slightly higher value of 0.07 W m^{-2} in this region (Clark et al., 1978).

Potential temperature profiles in the deep Venezuelan Basin were apparently relatively time-invariant in the 1930s, 1950s, and 1960s, with values approaching as cold as $\theta = 3.80$ °C near 5000 m during those decades (Worthington, 1966). However, a comparison of data in the Caribbean Sea from a 1958 International Geophysical Year (IGY) section nominally along 66°W with more recent data from the 1997 World Ocean Circulation Experiment (WOCE) hydrographic section A22 along nearly the same nominal longitude finds a statistically significant warming of $\Delta\theta = 0.041$ °C (along with a statistically insignificant freshening of $\Delta S = -0.0016$ PSS-78 in salinity) between 1958 and 1997 (Joyce et al., 1999). The differences are nearly constant in the vertical from the sill depth of 1815 m to the bottom. Joyce et al. (1999) attributed this change in the deep temperature to a long-term warming of the deep waters of the North Atlantic (Joyce and Robbins, 1996) that ventilate the deep basins of the Caribbean Sea.

In 2003, WOCE section A22 was reoccupied as part of the U.S. Repeat Hydrography Program in support of CLIVAR and CO_2 studies. Here a comparison of the 2003 and 1997 data is presented. The warming between 1958 and 1997 reported by Joyce et al. (1999) along 66°W continues through 2003 with slight freshening again observed. In addition, an analysis of historical temperature profiles from the World Ocean Database 2005 (Boyer et al., 2006) is in agreement with previous results (Worthington, 1966) that deep Caribbean Sea temperatures were steady from as early as the 1920s through the 1960s, and in fact into the 1970s, with a significant warming signal commencing only in the 1980s and continuing through 2003. Since deep basin temperatures do not appear to be in steady state, the heat budget for the Caribbean Sea below the sill depth is revisited here, with emphasis on the magnitude of vertical diffusivity needed to account for the observed temperature changes in the deep basins.

2. Data

In August 1997 high-quality Conductivity-Temperature-Depth (CTD) instrument data were collected from the surface to the bottom at stations in the Caribbean Sea as part of the occupation of WOCE Section A22, along nominal longitude 66°W. The stations were occupied at nominal horizontal spacing of 55 km, closer over rapidly varying bathymetry. Instrumental accuracies are thought to be 0.002 °C for temperature, 0.001 PSS-78 for salinity, and 2 dbar for pressure (Joyce et al., 1999). In 2003, the U.S. Repeat Hydrography Program reoccupied this section in support of CLIVAR and CO_2 science, crossing the Caribbean in October of that year. Accuracies of CTD data for the 2003 survey are thought to be similar to those in 1997 (http://cchdo.ucsd.edu). Standard Sea Water (SSW) batch P131 was used to standardize the salinity measurements in 1997, and SSW batches P140 and P141 were used to standardize the salinity measurements in 2003. Following Kawano et al. (2006), +0.0001 PSS-78 is added here to the 1997 salinity data and –0.0003 to the 2003 salinity data to account for careful laboratory assessments of differences among the SSW batches used.

Additional deep historical temperature profiles in the Caribbean Sea (Fig. 1) are obtained from the World Ocean Database 2005 (Boyer et al., 2006). Only data with good quality flags are considered for this analysis. To avoid variability associated with the deep inflow into the Caribbean, stations analyzed are limited to those south of 17°N within the 2000-m isobath of the Venezuelan and Columbian basins. In addition more than three temperature measurements below 2000 dbar are required for a profile to be used here. Depth data are converted to pressure and potential temperatures are estimated using the temperature and pressure data assuming a salinity of 34.98 PSS-78 (a value typical of the Caribbean Sea below 2000 dbar).

All profiles are subject to further screening prior to analysis, and data of poor quality discarded. In the deep Caribbean basins profiles of θ are approximately exponential (Ribbat et al. 1976; Fig. 2). To check for potential outliers, an exponential is fit to each θ profile versus pressure below 2000 dbar (Fig. 2). Stations with a standard deviation of the residual to the fit exceeding 0.02 °C are flagged. This threshold is about twice the magnitude of the expected accuracy of high-quality historical temperature data from Nansen bottle casts (Warren, 2008). Noise at the level of measurement accuracy is illustrated by physically implausible temperature inversions of about ±0.01°C present in some individual bottle casts (e.g., Fig. 2a). Similar inversions are not observed in CTD station data (e.g., Fig. 2b). In addition, any station with any parameter of its exponential fit that is an extreme outlier (greater than the third quartile plus three times the interquartile range or less than the first quartile minus three times the interquartile range of the parameter in question) is also flagged. Stations with flags are discarded only after being visually inspected and judged to be obviously anomalous.

Data quality varies by decade. This variation is reflected in the relatively high percentage of stations failing the screening process during the 1960s and 1970s. Of the 59 flagged stations, 31 are judged outliers. These outliers include 2 stations from the 1930s, 2 from the 1950s, 12 from the 1960s, and 15 from the 1970s, but none thereafter. After screening, 153 stations of acceptable quality remain between 1922 and 2003 (Fig. 1).

The 1950s data, mostly high-quality profiles gathered under the auspices of the IGY, have a much smaller range of deep temperatures compared to that of data from the 1960s and 1970s, which were collected by a number of different expeditions for varied purposes. The mean range in potential temperatures at pressures exceeding 3000 dbar using all 1950s data deemed useable collected in the basin is ~0.02 °C, about twice the expected error of a single careful reversing thermometer reading (Warren, 2008), while the mean range for the 1960s and 1970s is ~0.06 °C and ~0.07 °C respectively. All three of these decades have a wide spatial distribution in the basin. The mean range in the 1990s and 2000s is ~0.003 °C; however, these values are estimated using data from nine CTD stations in each decade collected along a single meridional section along 66°W. Like analysis of a similar line taken during the 1950s results in a mean range of ~0.014

°C, suggesting that at least for the decades prior to the 1990s, measurement accuracy may be responsible for much of the temperature variations reported at a given depth. The smaller variations seen in more recent decades are most likely owing to the advent of much more precise CTD instruments. Unfortunately, there were no similar sections along 66°W from the 1960s or 1970s available for comparison. Nonetheless, the range of the temperature data on deep isobars in any given decade appears primarily to reflect its measurement accuracies, at least prior to the 1990s.

3. Repeat section analysis

The most accurate estimates of property changes in the deep Caribbean Sea are probably afforded by closely spaced full water-column repeat CTD sections such as the 1997 and 2003 repeats of WOCE Section A22. Following Joyce et al. (1999), the analyses of the seven stations sampled in 1997 and again in 2003 along A22 between 12.5 and 16.5°N are carried out in pressure coordinates. The potential temperature and salinity data for each station are low-passed vertically with a 40-dbar half-width Hanning filter. The results are then interpolated to a 10-dbar-pressure grid. The vertically gridded data sets are then interpolated onto an evenly spaced latitudinal grid at 2' spacing using a space-preserving piecewise cubic Hermite interpolant at each pressure level. The horizontal gridding allows estimates of differences and degrees of freedom, while preserving the original variance of the data. The close grid spacing matches that of a high-resolution bathymetric dataset used here generated by merging satellite altimetry data with bathymetric soundings (Smith and Sandwell, 1997). The bathymetry from this dataset along the section is used as a mask to eliminate grid points where data have been interpolated to locations below the ocean floor.

The differences of these two gridded fields are averaged at each pressure level within the specified latitudes (Fig. 3). The 95% confidence limits for the mean differences are estimated following Johnson et al. (2008): First integral spatial scales for each quantity studied at each pressure level are estimated from integrals of autocovariances (e.g., Von Storch and Zwiers, 2001) in latitude. The effective numbers of degrees of freedom are then computed by dividing the latitude ranges sampled at each pressure level by the appropriate integral spatial scales. These effective degrees of freedom are used throughout the error analysis for the repeat sections, including applications of Student's t-test for 95% confidence limits.

The mean warming below the sill depth is about +0.010°C over the 6.2-year interval between the repeat occupations (Fig. 3a). This warming is statistically different from zero at the 95% confidence level. The warming is also much larger than the quoted instrumental accuracy of 0.002°C. There also appears to be about 0.001 PSS-78 in freshening between 1997 and 2003 (Fig. 3b). While this result is statistically significant in terms of signal-to-noise levels, the accuracy of each cruise is about 0.001 PSS-78, so it is possible that salinity measurement biases between the two cruises could be the source of this difference. If the salinity change were real, it would tend to augment the observed temperature change in reducing the density of water within the deep basins of the Caribbean Sea.

4. Historical data analysis

As detailed in Section 2, 153 historical stations (including data from the WOCE and CLIVAR/CO_2 occupations of WOCE section A22) pass a set of screening criteria (Fig. 1). These stations are located throughout the deep basins of the Caribbean Sea, except that they are limited to locations south of 17°N to avoid sampling inflow variability. The data from these stations, linearly interpolated in the vertical to a uniform pressure grid, are used to explore the temporal evolution of deep temperatures in the Caribbean Sea.

While there are a few stations in the 1920s and 1930s, most of which pass the screening criteria, it is not until the 1950s that sufficient data exist to construct decadal mean vertical profiles of potential temperature in the deep Caribbean (Fig. 4), using data throughout the deep basins. The mean vertical profiles of potential temperature versus pressure for the 1950s, 1960s, and 1970s are somewhat noisy and overlap in places. However, the 1980s mean curve appears warmer than those for the previous three decades by about 0.01°C throughout much of the water column below 2000 dbar, and that pattern continues into the 1990s and 2000s. In short, the deep Caribbean Sea appears to have been warming since the 1970s at a roughly steady rate of over 0.01°C decade^{-1}.

One might be concerned that these results could be aliased by horizontal spatial variability, since the station locations within the Caribbean Sea vary considerably by decade (Fig. 1). Previous studies in the Venezuelan and Columbian basins have found negligible deep horizontal gradients in water properties (Worthington, 1966; Ribbat et al., 1976; Joyce et al., 1999). Nonetheless, here we quantify gradients of potential temperature in latitude, longitude, and time by making linear fits of that quantity to these three parameters at various pressures at and below the sill depth for the Caribbean Sea using screened data as detailed below.

Data taken after 1980 clearly contain a temporal trend (Fig. 4) and are mostly confined to the eastern portions of the Caribbean Sea (Fig. 1), so only the pre-1980 data are fit in an attempt to avoid aliasing of large temporal trends into estimates of spatial gradients. Furthermore, while the pre-1980 data are better distributed in time and space than the post-1980 data, their distribution at pressures greater than 3500 dbar, where only few stations reach, is still too sparse to fit, so no fits are made for pressures greater than 3500 dbar. The 95% confidence intervals for these fits are estimated assuming that all stations are independent. As some station data may be correlated, these confidence intervals may be too small.

Meridional linear trends from the fits reverse sign with pressure and are not statistically significantly different from zero with respect to the formal 95% confidence limits at any pressure, so they are not considered further.

In contrast, both the zonal and temporal linear trends from the fits to the pre-1980 data (not shown) are small, but of the same sign at all pressures from 1833–3500 dbar. Both the zonal and temporal linear trends are also just statistically different from zero with respect to the formal 95% confidence intervals only over portions of this pressure range. The vertical mean of the temporal linear trend between 1833–3500 dbar is 0.0003 °C decade^{-1} prior to 1980. This temporal linear trend is many times smaller than the post-1980 warming. The vertical mean of the zonal linear trend between 1833–3500 dbar is 1×10^{-8} °C m^{-1} (temperatures increase toward the east). The vertical mean zonal linear trend is only about half of this value between 2500 and 3500 dbar. These zonal linear trends have only a small affect on the basin-mean calculations, as shown below.

An analysis of two different decadal basin-wide means at 3000 dbar illustrates the uncertainty in the results as well as the effect of the small zonal linear trends found in deep temperatures on the results (Fig. 5). The first means considered are the simple averages of the screened station data within each decade without regard to their spatial location. These means are identical to those in the decadal mean profiles (Fig. 4), with the addition of the value from the single 1922 station retained and the 1930s mean. To assess the uncertainties of these means, the 95% confidence intervals for each simple decadal average are estimated assuming all stations are independent. Recall that temporal variations in 95% confidence intervals are likely to be mostly owing to variations in instrumental accuracy and precision prior to the 1990s, as discussed in Section 2. No change is evident within the 95% confidence intervals for the decadal means of temperature data in the 1930s, 1950s, 1960s, or 1970s. However, clearly statistically significant warming occurs between the 1980s and the 1990s, and the 1990s and the 2000s.

To ensure that the small and marginally statistically significant zonal linear trends found in the deep basins are not significantly biasing these results, a second set of decadal means is computed (Fig. 5). The vertical mean of the 1833–3500 dbar zonal linear trends found in the pre-1980 data is applied to each station's potential temperature value at 3000 dbar to adjust it to a predicted value for longitude 66°W. This vertical mean of the zonal linear trend is larger than its value at 3000 dbar, so its application may overstate the effects of zonal temperature gradients on estimates of the basin-wide mean.

Because most of the post-1980 stations are taken along 66°W, these adjustments to account for the deep horizontal gradient in potential temperature have almost no effect on the means for these decades. However, the pre-1980 stations are often located somewhat to the west of 66°W, so the pre-1980 adjusted decadal means are slightly warmer than the simple pre-1980 decadal means. The effects of these adjustments on the results are slight shifts in some of the decadal means, but these shifts are small, and well within the 95% confidence limits of the simple average values.

Together geostrophy and mass continuity place a strong constraint on lateral density gradients within the deep Caribbean basins, enclosed as they are below 1815 m. For instance, a depth-independent lateral temperature difference of 0.03°C (about the size of the temporal increase estimated here) over the 3000-m interval between the sill depth and the bottom would require a geostrophic volume transport of 6×10^6 m^3 s^{-1} over that depth interval at 15°N, assuming no compensating salinity gradients and zero velocity at either the sill depth or the bottom. This current would be over fifty times the size of the inflow measured in 1991–1992 (MacCready et al., 1999). Given the requirement of mass continuity, it could only recirculate around the basin, and thus its signatures would have to be visible in the individual sections crossing the basin in the 1950s, 1990s, and 2000s. Depth-independent lateral temperature differences of this size are not evident in these individual sections, further supporting the finding of weak and barely statistically significant lateral temperature gradients in the analysis above.

5. Post-1970s deep heat budget

The observed warming rate of over 0.01°C decade^{-1} in the deep basins of the Caribbean Sea since the 1970s indicates an imbalance in the deep heat budget during this time period. What could be the source of heat for this deep warming? Below sill depth, there are only four terms in the heat budget. Geothermal heating at the bottom and vertical diffusion of temperature both act to warm the waters of the deep basins, whereas cold waters entering the deep basins through a deep sill and descending as an overflow plume that eventually spreads into the deep interior and upwells provide the only cooling.

Any imbalance in those three terms requires a departure from steady state, and a fourth term for time-dependent heat storage in the deep basins becomes necessary. Here, a heat budget including a heat storage term is essayed for the post 1970s time period, using available observed values. However, some of the observations are made over a small time window compared to the renewal time for the deep basins, introducing potential for errors.

If the deep Caribbean Sea is out of steady state and warming, as post-1970s observations suggest, then a depth integrated heat budget can be approximated by

$$\frac{1}{A_s}\int_{z=-b}^{z=-s}\rho c_p A\frac{d\theta}{dt}dz = \frac{F}{A_s}\rho c_p\left(\theta_o - \theta_s\right) + Q_{geo} + \rho c_p \kappa \left.\frac{d\theta}{dz}\right|_s, \qquad (1)$$

where ρ is the density of seawater, c_p its specific heat, A is the deep basin cross-sectional area at any given depth z, θ is potential temperature, t is time, $F = 0.11 \times 10^6\ \mathrm{m^3\ s^{-1}}$ is the volume flux of cold overflow water entering the Caribbean Sea near the sill depth as observed in 1991–1992 (MacCready et al., 1999), $Q_{geo} = 0.05\ \mathrm{W\ m^{-2}}$ is the average geothermal heating at the sea floor in the deep basins of the Caribbean Sea (Epp et al., 1970), and κ is the vertical diffusivity. The index b refers to the bottom, s the sill, and o the overflow, so $A_s = 1.06 \times 10^{12}\ \mathrm{m^2}$ is the cross-sectional area of the deep basins at the 1815-m sill depth, and $3.95 \leq \theta_s \leq 3.99$ °C is the potential temperature at sill depth, with the minimum value being typical of pre-1970s conditions, but then increasing by over 0.01°C decade^{-1} to the maximum value in 2003. The time-dependent top boundary condition implied by this temperature trend at the sill depth is neglected in the derivation of (1), and the ramification of this neglect is discussed in Section 6. The transport-weighted potential temperature of the overflow water in 1991–1992, $\theta_o = 3.876$ °C is estimated graphically from the figures of MacCready et al. (1999). The vertical potential temperature gradient at the sill depth, $d\theta/dz|_s = 3.0 \times 10^{-4}$ °C m^{-1} is estimated from linear fits to 1997 and 2003 CTD data within a 200-m window centered on the sill depth. The time rate of change of potential temperature, $d\theta/dt$, is estimated using the latitudinal mean change in temperature between the gridded 1997 and 2003 WOCE Section A22 along 66°W (Fig. 3).

The various terms in the heat budget for the deep basins of the Caribbean Sea, (1), can be estimated using the values given above. Proceeding from left to right, the heat storage term is 0.39 Wm^{-2}. The second term, the cooling by the overflow waters, has a range of –0.03 W m^{-2} to –0.05 W m^{-2}. A range is calculated because θ_s steadily increases beginning in the 1970s, but that range does not take into account variability in θ_o or F, which are derived solely from 1991–1992 observations. The third term, the geothermal heating, is Q_{geo} = 0.05 W m^{-2} (Epp et al., 1970). The overflow cooling and the geothermal heating appear to balance approximately, and are both much smaller than the heat storage term, which dictates that the fourth term must be in the range of 0.37–0.39 W m^{-2}, to roughly balance the heat storage term. This balance implies a vertical diffusivity in the range of $3.1 \times 10^{-4} \leq \kappa \leq 3.2 \times 10^{-4}$ m^2 s^{-1}.

6. Discussion

There are several sources of error in the post-1970s heat budget that bear further discussion. First, we have estimated the heat storage term of 0.39 W m^{-2} in (1) from the 1997 and 2003 repeat section data (Fig. 3), which are the most accurate. However, the deep Caribbean waters also appear to exhibit the most rapid rate of warming during this time period (Figs. 4 and 5). The warming rate between the 1970s and the 2000s appears to be about 2/3 of that from 1997 and 2003. Hence, the heat storage term for the entire period of warming could be as small as 0.27 W m^{-2}. Reducing this term would reduce the estimate of κ to about 2×10^{-4} m^2 s^{-1}.

Second, the basin-average value of geothermal heating, Q_{geo} = 0.05 W m^{-2}, could be too small. However, the highest values of ocean heat flux in the region, observed in the eastern Caribbean, only reach 0.07 W m^{-2} (Clark et al., 1978), and are still dwarfed by the heat storage term, even if it is reduced to its lower long-term value. While we are unaware of published heat flux values taken after the 1970s when the deep basin waters began to warm, the region is relatively stable geologically, making a recent increase in geothermal heating unlikely.

A third potential source of error in the heat budget is that the derivation of (1) makes a simplifying assumption that the top boundary condition for potential temperature in the basin at the sill depth, θ_s, is constant. This assumption is not correct because θ_s steadily increases after the 1970s (Fig. 4). The simplification is finessed in Section 5 by using the observed range for decadal θ_s variations. However, a warming top boundary condition will tend to heat the deep basin below, reducing the vertical diffusivity required to balance the heat budget. To correctly determine the vertical diffusivity, a more complete time-dependent model would be required.

The post-1970s heat budget is essayed in Section 5. However, prior to the 1970s the deep basin heat budget appears to be in steady state, so the balance of terms was likely to have been quite different then. For the heat storage term to be negligible before the 1970s, at least one of the other three terms would have to have changed. What was different prior to the 1970s and what caused the change? As discussed previously, the geothermal heating term has probably not varied significantly in recent history, leaving the diffusivity term or the inflow term to be the more likely cause of the variation.

If the pre-1970s inflow of water to the basin were some combination of colder and larger than the 1991–1992 values of MacCready et al. (1999) used in Section 5, then the cooling term in (1) could have been larger prior to the 1970s, obviating the need for a heat storage term. Indeed, Joyce et al. (1999) suggest that the source waters entering the deep Caribbean through the Anegada–Jungfern Passage have warmed, citing a steady mid-depth warming from the 1920s through 1990 near Bermuda (Joyce and Robbins, 1996).

Furthermore, a box model based on early 1970s ^{14}C and other water properties in the deep Caribbean (Ribbat et al., 1976) supports the idea of a colder or stronger deep inflow into the Caribbean prior to the 1970s, as well as large vertical diffusivities similar to those required for the post-1970s heat budget (Section 5). Ribbat et al.'s (1976) estimates for the pre-1970s deep inflow result in a cooling term in equation (1) as high as 0.26 W m^{-2} near the end of the period when the basin was in steady state. This term would roughly balance the vertical diffusivity term of 0.27 W m^{-2} using $\kappa = 2 \times 10^{-4}$ m^2 s^{-1}. The geothermal warming term of 0.05 W m^{-2} is small relative to the uncertainties in the two other terms. Ribbat et al.'s (1976) calculations are for the deep Venezuelan basin alone. We are unaware of any direct observations that would support or rule out a larger or colder inflow prior to the 1970s. However, the observations and analysis of Ribbat et al. (1976) do support the ideas that the inflow into the Caribbean was larger and colder in past years, and that a vertical diffusivity of 2×10^{-4} m^2 s^{-1} could be appropriate.

However, the Anegada–Jungfern Passage is far from Bermuda where warming is quantified (Joyce and Robbins, 1996), and presumably it is Labrador Sea Water (LSW) within the Deep Western Boundary Current (DWBC) that ventilates the deep Caribbean. Relatively cool, fresh, CFC-rich LSW started forming in 1988 during a period of vigorous convection that continued through 1996 (Yashayaev, 2007). This vintage of LSW began to arrive in the DWBC off Abaco at 26.5°S (Molinari et al., 1998) starting in the mid 1990s, and shortly thereafter off French Guiana at 7°N (Freudenthal and Andrié, 2002). One might think that the reported cooling and freshening of LSW within the DWBC should be reflected in the differences in deep Caribbean temperatures between 1997 and 2003. However, the cooling and freshening reported is on isopycnals, and does not necessarily imply cooling at the sill depth. In addition, the long residence time of the deep Caribbean Sea may act to filter out decadal variations in the inflow (Joyce et al., 1999).

An additional puzzling feature remains in the observations of post-1970s deep Caribbean Sea warming. Consistent with the previous analysis comparing 1958 to 1997 data (Joyce et al., 1999) the warming appears almost constant with depth from decade to decade since the 1970s (Fig. 4). Measurement errors could be the cause of such strikingly depth-independent changes. However, the mean temperature differences between 1997 and 2003 alone far exceed the quoted instrumental accuracies for measurements taken in those years, and the post-1970s increases appear steady over three decades despite the varied sources of the observations over this time period.

Nonetheless, one might expect that if warmer overlaying water at the sill depth of the basin were a substantial contributor to the deep warming, there would be a time delay between changes observed near the sill depth and those near the bottom of the Caribbean Sea, inducing a depth-dependent temperature change. Instead, the decadal warming trend is nearly uniform below the sill depth. If measurement errors are not the cause of this vertically uniform temperature increase, a balance among the top boundary condition, vertical diffusion, geothermal heating, and the inflow would seem necessary to maintain it. A more complex model of the heat budget might help to investigate this puzzle.

The data used in this study are heterogeneous in space, time, and measurement technique. These heterogeneities suggest some caution in interpretation of the analyses presented here. While the deep warming estimated between 1997 and 2003 from the highly accurate repeat CTD section data taken in these years clearly exceeds sampling and measurement errors, these data are geographically limited to a single meridian, 66°W, near the eastern end of the deep Caribbean Sea. In contrast, the earlier pre-1990s primarily bottle data, from which the deep lateral temperature gradients within the basin are estimated to be small by others with that result reaffirmed here, better sample the full geographical extent of the deep Caribbean Sea, but have larger measurement errors than the more recent data.

Nonetheless, the statistically significant warming presented here suggests large physical changes in the deep Caribbean basins. When changes from below sill depth seen along A22 between 1997 and 2003 are applied to the whole deep Caribbean, a heat gain of 0.39 W m^{-2} results. As previously mentioned, this amount is considerably more heat than the 0.05 W m^{-2} estimated for geothermal heating at the bottom (Epp et al., 1970). In fact, this regional rate of deep heat storage increase exceeds estimates of global heat uptake from the surface to 3000 m over the past 40 years (Levitus et al., 2005).

However, the deep Caribbean only accounts for a small part of the Earth's surface area, so the contribution of this warming to the global heat budget is relatively small on its own.

Assuming a constant deep salinity in the Caribbean, the warming below 2000 dbar between 1997 and 2003 accounts for thermosteric sea level rise at a rate of about 0.008 m decade^{-1} over regions of the Caribbean Sea with bottom depths around 5000 m. The rate would be smaller in shallower regions. If the slight freshening of 0.001 PSS-78 over the 6.2 years is real, adding the halosteric effect of that change to the sea level rise budget below 2000 dbar would increase the rate to about 0.012 m decade^{-1} in the deeper parts of the Caribbean Sea. This rate of change is a significant fraction of the total rate of global sea level rise of 0.03 m decade^{-1} since 1993 (Nerem et al. 2006), so at least in the Caribbean, the bottom half of the ocean appears to be a significant contributor to sea level rise budgets.

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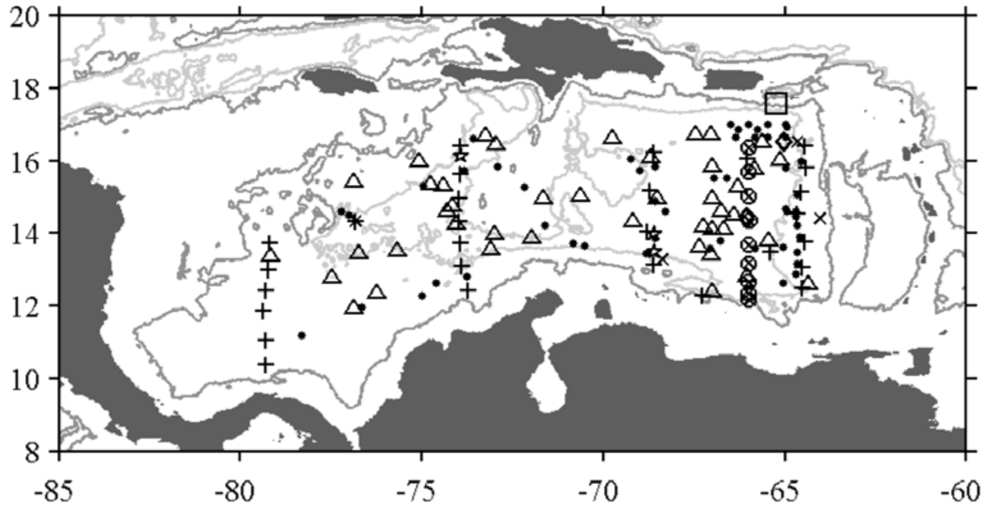

Fig. 1. Locations of hydrographic station data used in this analysis of deep property changes in the Venezuelan and Columbian basins of the Caribbean Sea from the 1920s (asterisks), 1930s (pentagrams), 1950s (plusses), 1960s (dots), 1970s (triangles), 1980s (diamonds), 1990s (crosses), and 2000s (circles). The 2000-m (dark gray line) and 4000-m (lighter gray line) isobaths are contoured and a box is plotted over the 1815-m deep sill of the Anegada–Jungfern Passage. The 153 stations shown, including 9 each from the 1997 and 2003 occupations of WOCE section A22 along 66°W, pass a set of screening criteria described in the text.

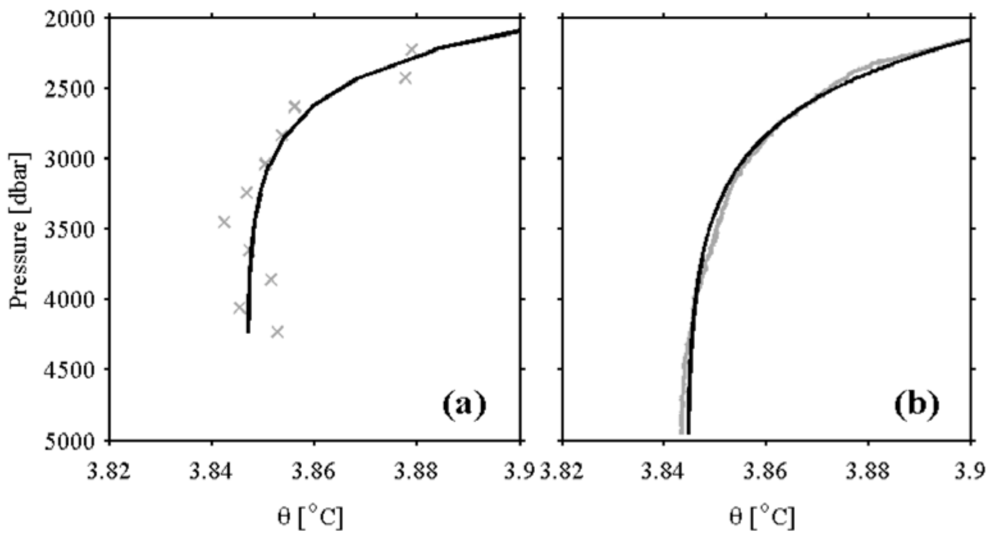

Fig. 2. Typical examples of exponential fits (dark lines) to (a) Nansen bottle station data (light crosses) and (b) CTD station data (light line) within the deep Caribbean Sea.

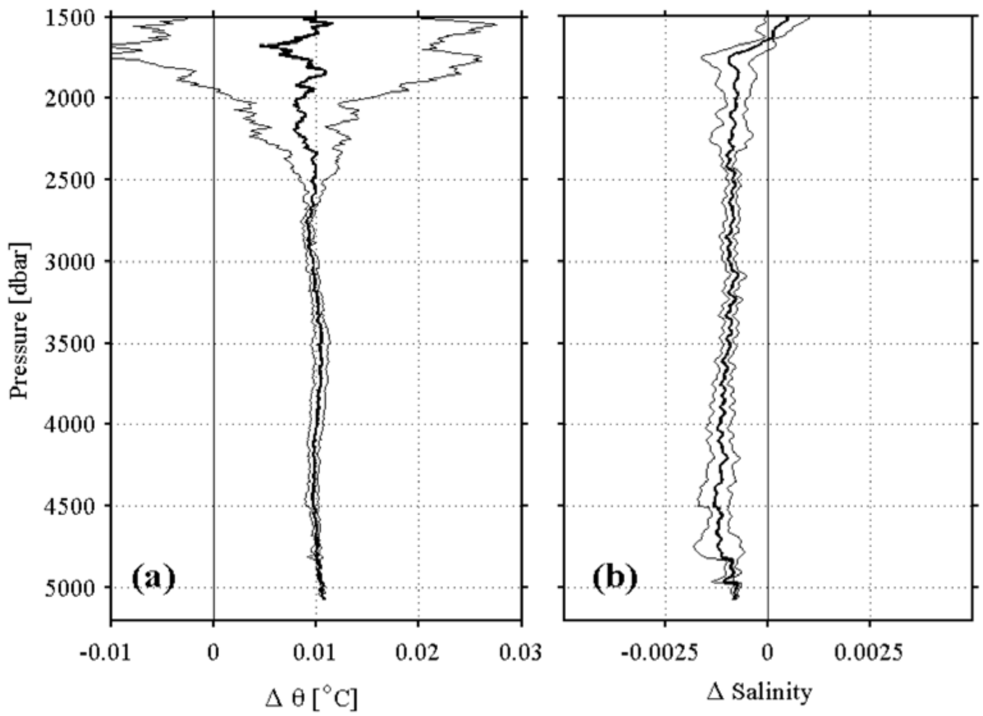

Fig. 3. Mean difference (black lines) of (a) potential temperature and (b) salinity with 95% confidence intervals (grey lines) computed by subtracting 1997 data of WOCE section A22 along 66°W gridded against pressure and latitude from 12.5 to 16.5°N from the similarly gridded 2003 section data and then taking the latitudinal average as a function of pressure. Estimation of 95% confidence intervals is described in the text. Potential temperature and salinity axes are scaled so their contribution to density is equal in terms of their distance from zero (black vertical lines).

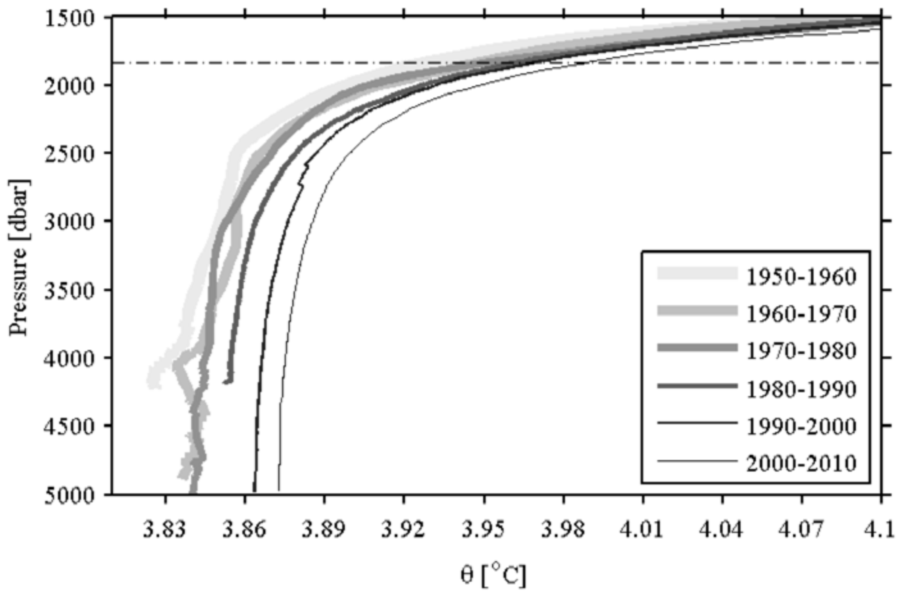

Fig. 4. Mean potential temperature profiles from screened historical data in the Caribbean Sea linearly interpolated as a function of pressure averaged by decade from the 1950s through the 2000s with the sill depth (dashed horizontal line) indicated.

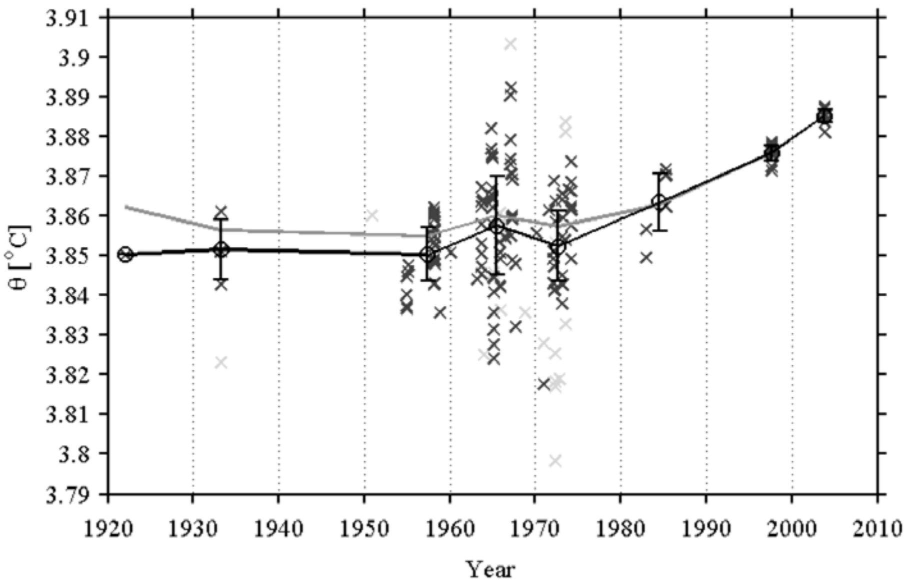

Fig. 5. Potential temperature values from historical station data in the deep basins of the Caribbean Sea linearly interpolated to 3000-dbar pressure (crosses). Lighter crosses denote values from historical stations that did not pass the screening and are therefore not used in the analysis here (see text). One discarded point (θ = 3.78 °C) during the 1930s and three (θ = 3.92, 3.97, and 3.97 °C) during the 1970s lie outside the temperature range plotted here. Simple average potential temperature values for each decade are plotted at the average station time for that decade (circles connected by solid dark line) with 95% confidence intervals (error bars). Alternate decadal averages constructed by adjusting potential temperature values to a uniform longitude of 66°W using a 1833–3500-m vertical-mean zonal linear trend in potential temperature estimated from pre-1980 station data (see text) are also presented (gray line).